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CP VIOLATION AT HIGH ENERGIES*

Mary K. Gaillard
Fermi National Accelerator Laboratory, Batavia, Illinois 60510
and
LAPP, Annecy-le-Vieux, France

ABSTRACT

The high energy sector of gauge theories with hard CP violation is discussed with emphasis on "strong" CP violation and baryon number generation.

INTRODUCTION

Existing data are compatible with the "standard" GWS[1]-GIM[2]-KM[3] model of weak interactions: an $SU(2)_L \otimes U(1)$ electroweak gauge theory spontaneously broken via the introduction of (minimally) one Higgs doublet whose Yukawa couplings to fermions are responsible for quark masses and their generalized, complex Cabibbo angles which are in this model the only source of CP violation. The low energy phenomenology of this model has been reviewed by Lin-Li Wang; I shall instead discuss ways of probing the high energy sector using the standard model and its minimal extension to a unified theory of strong and electroweak interactions as a reference point.

One low energy probe of the high energy sector is provided by the experimental limit on the "strong" CP violation parameter θ which appears[4] via non-perturbative topological effects in the effective QCD Lagrangian:

$$\mathscr{L}_{QCD} \ni \theta \frac{\alpha_s}{\pi} \tilde{F}_{\mu\nu}{}^{i} F_i{}^{\mu\nu} \tag{1}$$

the most stringent bound on θ is provided by the low experimental limit[5] on the neutron dipole moment which leads to the estimate[6]

$$\theta < \text{a few} \times 10^{-9} \quad . \tag{2}$$

Since in the standard model defined above CP violation is "hard," θ is infinitely renormalized and the cut-off Λ which must be introduced to render it finite might indicate an energy level at which new physics should intervene. However, the GWS-GIM-KM model requires only

$$\Lambda < \exp(10^{25})\ \text{GeV} \quad , \tag{3}$$

while we expect new physics at considerably more modest energies: at least at 10^{19} GeV where gravitational effects become important, and more probably at 10^{14} GeV as suggested by grand unified theories (GUTs).

The "minimal" GG[7]-BEGN[8] model for grand unification is a straightforward extension of the "standard" electroweak model, namely SU(5) with the Higgs sector restricted to an adjoint to provide the

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The "minimal" GG[7]-BEGN[8] model for grand unification is a straightforward extension of the "standard" electroweak model, namely SU(5) with the Higgs sector restricted to an adjoint to provide the initial breaking to $SU(3)_c \otimes SU(2)_L \otimes U(1)$ and (minimally) a single 5-plet containing the electroweak doublet whose complex Yukawa couplings again provide quarks masses and mixing angles and the only source of CP violation. One might hope that further unification might ease the "strong" CP problem, but it turns out that this minimal version slightly aggravates it. More generally, the concept of grand unification leads naturally to further probes of the high energy sector: the low energy probe provided by baryon decay as well as a high energy probe provided by cosmological CP violation which we hope will account for the observed baryon-to-photon density ratio:

$$n_B/n_\gamma \simeq 10^{-9\pm1} \quad . \tag{4}$$

Efforts to explain the number (4) suggest that the minimal GUT is in fact insufficient; this result feeds back to the renormalization of θ in an essentially model-independent way and renders the constraint (2) more interesting.

θ-RENORMALIZATION

We define the strong interaction Lagrangian by taking the quark mass matrix to be real and diagonal, and—on the grounds that it is experimentally tiny—the θ parameter to vanish in the absence of weak radiative corrections. The CP violating property of the latter will induce a non-vanishing θ; in particular the renormalied mass matrix $M_{ren.}$ must be rediagonalized at each order in electroweak perturbation theory. Since CP violation introduces complex matrix elements which are logarithmically divergent, a redefinition of the quark basis so as to give a real, diagonal mass matrix involves a chiral transformation which, because of the anomolous divergence of the flavor singlet axial current, induces[9] a correspondingly divergent renormalization of θ:

$$\delta\theta = \text{Arg det } M_{ren.} \equiv a \ln \Lambda/m_N \tag{5}$$

The bound (2) then implies a limit on the cut-off parameter:

$$\Lambda < m \exp(10^{-9}/a) \quad , \tag{6}$$

which might be interpreted as the energy where new physics must come into play. This is analogous to the cut-off of a few GeV required to make, say, the quadratically divergent amplitude for $K_L \to \mu\mu$ compatible with experimental data in pre-GIM days, assuming vanishing strangeness changing neutral currents in lowest order weak interactions. In that case new physics—namely charm—did indeed appear to provide the needed cut-off. A more modern formulation would be to express a "running" $\theta(m) = a \ln \mu/m$ in terms of the scale[10] μ where an as yet unknown symmetry principle requires it to vanish.

In the "standard" model, and in the quark basis where electroweak gauge couplings are flavor diagonal, the Yukawa couplings are specified by two arbitrary complex coupling matrices:

$$\mathscr{L}_Y = (\bar{\psi}_L\cdot\phi)G_k\psi_R^k + (\bar{\psi}_L\cdot\tilde{\phi})G_a\psi_R^a + \text{h.c.} \qquad (7)$$

where $\psi_L^T=(\psi_L^a,\psi_L^k)$ is an electroweak doublet, the indices a and k denote "anoquark": $\psi_a^T=(u,c,t,\ldots)$ and "cathoquark": $\psi_k^T=(d,s,b,\ldots)$ vectors in flavor space, and $\tilde{\phi}=-i\,\tau_2\phi^*$. The mass matrices are generated by the usual shift $\phi=H+\langle\phi\rangle$ of the Higgs doublet with $\langle\phi^T\rangle = (0,v/\sqrt{2})$. A general complex square matrix can be written in terms of a diagonal matrix multiplied on the left and on the right by independent unitary matrices:

$$G_k = \frac{\sqrt{2}}{v}\,U_1^\dagger U_c M_k U_2 \quad , \quad G_a = \frac{\sqrt{2}}{v}\,U_1^\dagger M_a U_3 \quad . \qquad (8)$$

Since U_i, i=1,2,3 can be absorbed into the definitions of the quark fields while leaving the gauge couplings invariant, the only observables in (8) are the mass matrices $M_{k,a}$ and the Cabibbo matrix U_c which appears in the charged current matrix as well as the (unphysical) charged Higgs coupling after redefinition of ψ_L^k so as to give a[11] diagonal zeroth order mass matrix M_0. The renormalized mass matrix is given by the sum of radiative corrections to the quark propagator with one mass insertion and is in general complex:

$$\mathscr{L}_{mass} = \bar{\psi}_R M_{ren.}\psi_L + \text{h.c.} \quad ; \quad M_{ren.} \equiv M_0(1+C) \quad , \qquad (9)$$

and the change in θ induced[10] by the chiral transformation which makes M_{ren} real and diagonal is

$$\delta\theta = \text{Arg Det } M_{ren.} = \text{Arg Det}(1+C) = \text{ImTr}\ln(1+C) = \text{ImTr}C + \ldots \qquad (10)$$

The multiple GIM-type cancellations associated with CP violation in the KM model require quark mass factors to appear in ImC. Since C is at most logarithmially divergent any additional mass insertions render it finite so that the divergent part can arise only from multiple (physical or unphysical in a renormalizable gauge) Higgs exchange. Inspection shows[10] that the first non-vanishing divergent contribution appears for six Higgs loops (plus one U(1) loop without which the ano- and catho-quark contributions would cancel identically), e.g.:

$$\delta\theta_{inf} \propto \text{ImTr}(U^\dagger M_a^4 U M_k^4 U^\dagger M_a^2 U M_k^2) \quad . \qquad (11)$$

Finite contributions occur in a lower order giving[10]

$$\delta\theta = \delta\theta_{inf} + \delta\theta_{fin} \quad , \quad \delta\theta_{fin} \sim \left(\frac{\alpha}{\pi}\right)^2\left(\frac{m_q}{m_W}\right)^4 \sim 10^{-16}$$

$$\delta\theta_{inf} \sim \left(\frac{\alpha}{\pi}\right)^7\left(\frac{m_q}{m_W}\right)^{12} \ln(\Lambda/m) \sim 10^{-34}\ln(\Lambda/m) \quad , \qquad (12)$$

so that $\delta\theta<10^{-9}$ as long as $\ln(\Lambda/m)\lesssim10^{25}$. Other sources of CP-violation such as renormalization[12] of the di-gluon operator in

Eq. (1) involve similar traces of quark loops with Higgs exchange and give similar results.[13]

THE MINIMAL GUT

In the GG-BEGN model there are again two independent Yukawa coupling matrices:

$$\mathscr{L}_Y = 10_L^T\, C\, G_a\, 10_L\, H + \bar{5}_R\, G_k\, 10_L\, \bar{H} + \text{h.c.} \tag{13}$$

where 10 and 5 denote the conventional quark multiplets in SU(5). Again expressing the coupling matrices in terms of real, diagonal mass matrices

$$G_k = W\, M_k\, U_c^\dagger V \quad ; \quad G_a \equiv G_a^T = V^T S\, M_a V \quad , \tag{14}$$

we see that the unitary matrices W and V may be absorbed in the definition of the 5-plet and 10-plet, respectively, while the symmetry of G_a

$$G_a G_a^\dagger = G_a^T G_a^* = (G_a^\dagger G_a)^* \tag{15}$$

requires that S commute with M_a, so it is diagonal in the same basis:

$$S M_a^2 S^\dagger = M_a^2 \quad ; \quad S_{ab} = e^{i\phi_a}\delta_{ab} \quad . \tag{16}$$

Since an overall common phase may again be reabsorbed, we are left with[8,14,15] ($N_{generation}$ - 1) observable phases in addition to the Cabibbo parameters which include one observable phase for three generations.

Immediate consequences of the above analysis are that the Cabibbo angles for baryon decay are completely determined[8,14,16] in the minimal model, and that no CP violation can occur in lowest order since the effective Lagrangian is simply multiplied by an overall phase:[14] $e^{i\phi_1}$. Thus detailed studies of nucleon decay can in principle provide a test of this model, although deviations from its predictions are unfortunately expected to be small in many more general models.

A further consequence is that infinite θ renormalization will occur in a lower order[10] because a) the six-quark model contains two new phases which are unconstrained by low energy data, b) the presence of only the four heaviest quarks need be felt to generate CP violating effects and c) the presence of a new vertex, namely $q+H\to\bar{q}$ permits more complicated structures for the relevant trace; one finds,[15] e.g.:

$$\delta\theta_{inf} \propto \mathrm{ImTr}(M_a^3 S U M_k^2 U^\dagger M_a S^\dagger U^* M_c^2 U^T) \quad . \tag{17}$$

Inserting the appropriate masses and Cabibbo parameters, one sees that the θ renormalization is enhanced relative to the previously evaluated K-M case by a factor

$$\left(\frac{\delta\theta_{KM}}{\delta\theta_{GUT}}\right)_{inf} \sim \theta_c^2\left(\frac{M_t M_c M_s^2}{M_W^4}\right)\left(\frac{\alpha}{\pi}\right)^3(3)^8 \sim 10^{-12} \quad . \tag{18}$$

where the factor $(3)^8$ takes into account quark mass renormalization relative to their low energy values which were used in the estimate (12). A plausible guess is that Λ lies in the expected range of new physics $\Lambda\sim(10^{15}-10^{19})$GeV, so that $\delta\theta_{GUT}^{inf.}\sim 10^{-20}$ which is still safe.

BARYON NUMBER GENERATION

As discussed by a number of authors[17] GUTs contain the three ingredients necessary for generating a calculable net baryon number as first enumerated by Andrei Sakharov:[18] CP violating interactions, baryon number violating interactions, and a non-equilibrium epoch for the latter. Within the context of present theories, the dominant mechanism is believed to be the decay of superheavy Higgs bosons ($M_H\sim 10^{0\pm 2}$ M_X where $M_X\sim 10^{15}$ GeV are superheavy GUTs gauge vectors) at a temperature $T\lesssim 10^{14}$ GeV where baryon number violating forces drop from thermal equilibrium. As a first approximation, the baryon-to-photon density ratio (4) is simply given by

$$(n_B/n_\gamma)_{H\text{-decay}} \sim \left(\frac{g_H}{g_{tot}}\right)(\Delta B)_H \quad , \tag{19}$$

where g_H and g_{tot} are (essentially) the numbers of helicity states of scalars and of all particles in the theory, and $(\Delta B)_H$ is the baryon asymmetry intrinsic to Higgs decay. Since in the quark basis where gauge couplings are diagonal CP violation is confined to the Yukawa couplings, the leading order contribution to $(\Delta B)_H$ can be obtained by considering only Higgs-exchange radiative corrections to the $H\to f_1 f_2$ vertex. Summation over fermion final states reduces the calculation to the trace of a fermion loop with all possible scalar vertices inserted, just as in the calculation of $\delta\theta_{inf}$, and in the minimal GG-BEGN GUTs model the leading contribution is just proportional to the expression (17). Then one finds[15]

$$\Delta B = \frac{\Gamma(H\to B)-\Gamma(H\to -B)}{\Gamma(H)} \sim 10^{-1}\alpha^4\left(\frac{M_b^4 M_t^3 M_c}{M_W^8}\right)\Big/\alpha(M_t/M_W)^2 \sim 10^{-14}, \tag{20}$$

where the factor 10^{-1} arises from Cabibbo angles. Since one expects $g_H/g_{tot}\sim 10^{-2}$, the experimental number (4) requires a much larger value: $\Delta B\sim 10^{-7\pm 1}$.

In fact, there are various effects which tend to decrease n_B/n_γ relative to the simple estimate (19). Baryon number violating fermion-fermion scattering can wash out[19] the ΔB generated by Higgs decay in the non-equilibrium epoch; if the mass of the GWS Higgs doublet is sufficiently close to the Coleman-Weinberg value[20] of about 10 GeV, the breakdown of $SU(2)_L \otimes U(1)$ to $U(1)_{em}$ will be associated with a reheating which will further dilute[21] n_B/n_γ. So we

probably should require $(\Delta B)_H \gtrsim 10^{-5\pm1}$, which is nine orders of magnitude larger than the value (20) obtained in the minimal GG-BEGN model.

There are various possibilities for increasing the minimal model prediction (20). One would be simply to add arbitrarily heavy fermion generations. However, this is disfavored by a number of arguments. The successful calculation[8,22] of (M_b/M_c) and astrophysical arguments[23] on the number of neutrinos favor three or at most four generations of not-too-heavy $(M \lesssim M_W)$ fermions, while very heavy fermions $(M \gtrsim M_W)$ with the usual $SU(3)_c \otimes SU(2)_L \otimes U(1)$ quantum numbers would induce unacceptable radiative corrections to the relative strengths of the neutral- and charged-current fermi coupling constants[24] and to the Higgs potential,[25] rendering the observed vacuum unstable. A more acceptable modification is simply to add more super-heavy scalars. These need not be "Higgs" scalars in that they could have vanishing vacuum expectation values, but would have arbitrary complex Yukawa couplings, unconstrained by low energy phenomenology, i.e, unrelated to quark masses and mixing angles. On general grounds, a non-vanishing ΔB can be induced only[26] at 4th order in the Yukawa couplings. Systematic analysis[26] of possible decay channels shows that with the range of masses and couplings expected in a general GUT framework one can obtain $(\Delta B)_H = 10^{-10} - 10^{-6}$, by adding more scalars to the minimal SU(5) GUT, and $(\Delta B) = 10^{-6} - 10^{-2}$, if a more complex structure for the gauge group is introduced.

The conclusion is that GUTs do indeed provide the possibility of a quantitative understanding of the density ratio (4). Recall, however, that the calculation of $\delta\theta_{inf}$ is essentially the same as that of $(\Delta B)_H$. The first is the imaginary part of scalar-exchange radiative corrections to a mass insertion on a fermion loop divided by the uncorrected mass insertion; the second is the imaginary part of the same corrections to a Yukawa coupling divided by the uncorrected Yukawa coupling. If we complicate the scalar sector of the theory so as to jack up ΔB by nine orders of magnitude relative to (20), we expect that in the same theory we should find a corresponding increase in (18), giving $\delta\theta_{inf} \sim 10^{-11\pm?}$, for a cut-off $(\Lambda \sim 10^{15} - 10^{19})$GeV. Since there are undoubtedly errors of an order of magnitude or so in this estimate and in the "experimental" limit (2), the latter constraint starts to become interesting.

The analysis of both phenomena could be complicated by the presence of super-heavy fermions carrying exotic $SU(3)_c \otimes SU(2)_L \otimes U(1)$ quantum numbers which are to be expected in the framework of a truly unified, minimal parameter theory. Hopefully these would provide the desired "initial condition" $\theta(\mu \sim 10^{15} - 10^{19}\,\mathrm{GeV}) \equiv 0$, while dropping from equilibrium sufficiently soon to have no effect on (or perhaps give an additional contribution to) the value of ΔB generated by scalar decays. An alternative picture is one in which CP conservation is broken only "softly", as discussed in the following talk.

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